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(54) **BURIED ANODE LITHIUM THIN FILM BATTERY AND PROCESS FOR FORMING THE SAME**

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205/59

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429/162, 231.1, 231.2, 231.95, 245, 322;
205/57, 59

(56) **References Cited**

U.S. PATENT DOCUMENTS

4,003,753 A 1/1977 Hall
5,338,625 A 8/1994 Bates
5,489,492 A 2/1996 Asami et al.

5,512,387 A 4/1996 Ovshinsky
5,569,520 A 10/1996 Bates
5,612,152 A 3/1997 Bates
5,871,865 A 2/1999 Barker et al.
5,895,731 A 4/1999 Clingempeel
6,048,645 A 4/2000 Saidi et al.
6,090,504 A 7/2000 Sung et al.
6,168,884 B1 1/2001 Neudecker et al.
2002/0018935 A1 2/2002 Okada

FOREIGN PATENT DOCUMENTS

EP 0 689 260 A1 6/1994
WO WO 00/60689 10/2000

OTHER PUBLICATIONS

Chem. Abstr. (1997) Par. 451512.A publication by Parks et al., titled, "A study on the fabrication of lithium thin-film batteries.", See abstract.

Chem. Abstr. (1997) Par. 626809.A publication by Parks et al., titled, "A study on the fabrication of electrochemical characterization of lithium thin-film batteries.", See abstract.

International Search Report of PCT/US01/44025, Published in WO 03/43108, May 22, 2003.

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(57) **ABSTRACT**

A reverse configuration, lithium thin film battery (300) having a buried lithium anode layer (305) and process for making the same. The present invention is formed from a precursor composite structure (200) made by depositing electrolyte layer (204) onto substrate (201), followed by sequential depositions of cathode layer (203) and current collector (202) on the electrolyte layer. The precursor is subjected to an activation step, wherein a buried lithium anode layer (305) is formed via electroplating a lithium anode layer at the interface of substrate (201) and electrolyte film (204). The electroplating is accomplished by applying a current between anode current collector (201) and cathode current collector (202).

36 Claims, 2 Drawing Sheets

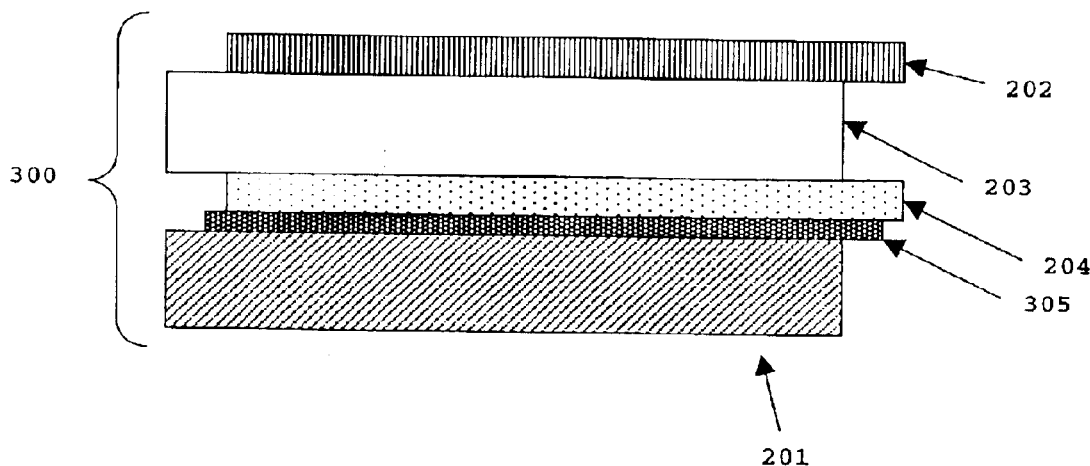


Figure 1 – Prior Art

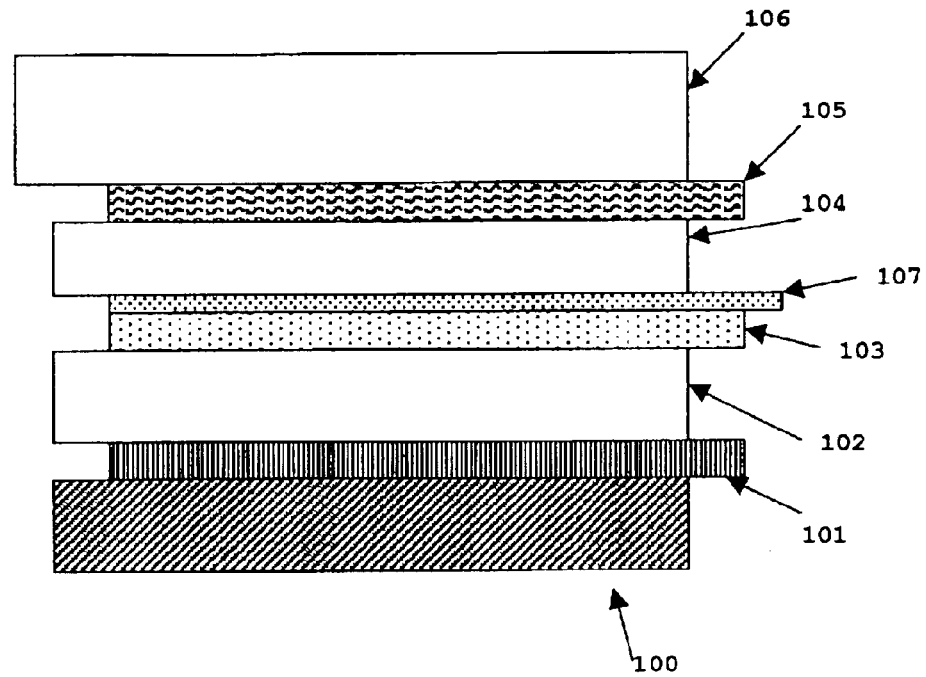


Figure 2

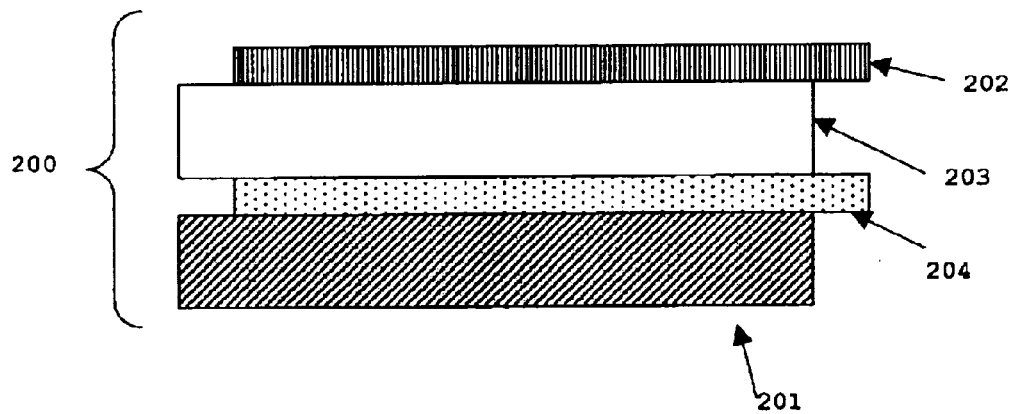


Figure 3

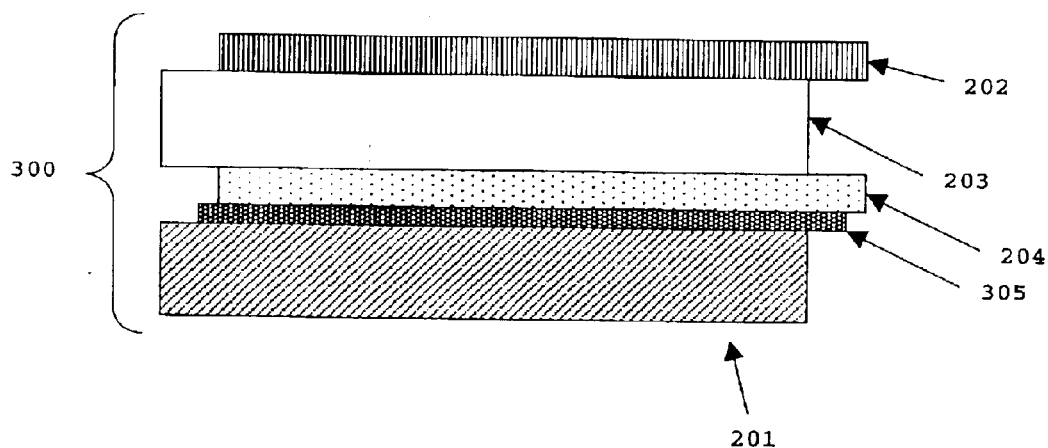
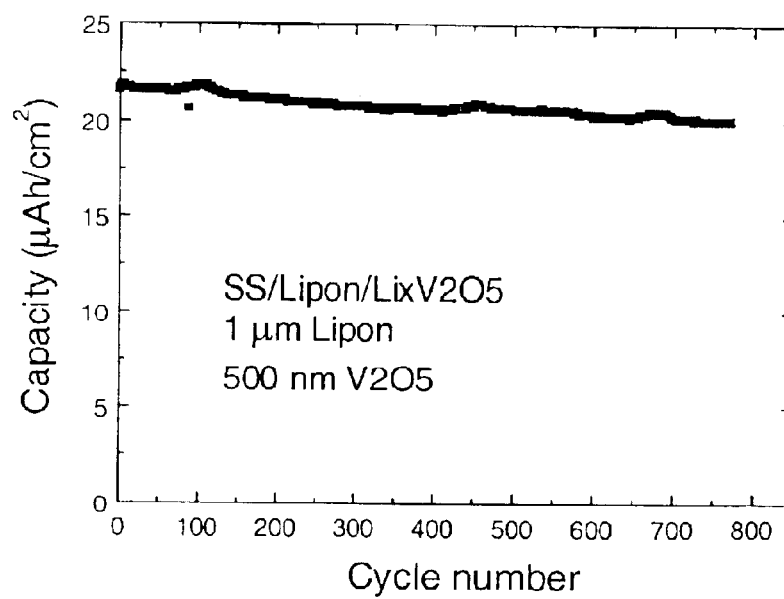


Figure 4



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BURIED ANODE LITHIUM THIN FILM BATTERY AND PROCESS FOR FORMING THE SAME

CONTRACTUAL ORIGIN OF THE INVENTION

The United States Government has rights in this invention pursuant to Contract No. DE-AC36-99GO-10337 between the United States Department of Energy and the Midwest Research Institute.

TECHNICAL INVENTION

This invention relates to the fabrication of lithium thin film secondary batteries.

DISCLOSURE OF INVENTION

Batteries are galvanic electrochemical cells which store and supply electrical energy as a product of a chemical reaction. In their simplest conceptualization, batteries have two electrodes, one that supplies electrons by virtue of an oxidation process occurring at that electrode, termed the anode (hereinafter, "anodic processes"), and a second one that consumes electrons by virtue of a reduction process occurring at that electrode, termed the cathode (hereinafter, "cathodic processes").

There are two broad classifications of batteries, primary batteries and secondary batteries. In primary batteries, either the anodic process, or the cathodic process, or both are irreversible, as defined for electrochemical processes. For this reason, once the reagents participating in the reactions are by-and-large consumed, the battery can't be returned to a charged state by electrochemical means.

In secondary batteries the electron producing and consuming reactions are for the most part reversible, as defined for electrochemical processes, and therefore such a battery can be cycled between a charged and discharged state electrochemically.

The reactions employed in batteries to produce and consume electrons are redox reactions. A pair of such reactions is called a redox couple. Each redox reaction is termed a half cell, with two half cells constituting a simple battery when the half cells are placed in ionic communication such that voltage potential appears between the electrodes of the half cells. Typically, the electrodes of several sets of half cells are electrically coupled together in either series or parallel configuration to supply a greater voltage or a greater current, or both than that which is available from a single set of half cells.

The voltage potential of a simple battery (a single set of half cells) is fixed by the set of redox couples chosen to produce and consume electrons. The redox couples are chosen such that the potential energy of the electron producing reaction yields electrons of sufficient potential energy to supply electrons to the electron consuming reaction. The electromotive force (emf) supplied by the battery is the difference between the potential energy of the electrons produced by the electron producing reaction and that required of the electrons consumed by the electron consuming reaction. As electrons are transferred from the electron producing reaction to the electron consuming reaction, charge within the half cells in which these reactions are carried out is balanced by the movement of ions between the half cells.

Ion batteries utilize materials in their construction that exhibit low resistance to ion movement through and within their structure. Thus, ion batteries improve the efficiency of

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storing and transferring electrical energy by reducing the resistance that ions must overcome at the interfaces of the various phases within the battery, and improve energy storage capacity by utilizing materials which do not polarize, and therefore during charge movement do not build up space charge regions which contribute resistance to charge movement within the battery. This feature tends to permit a higher density of charge species to be moved within a given volume of an ion battery than is possible with conventional materials. Additionally, thin film techniques permit the formation of very thin electrolyte layers separating the redox couples, further reducing resistance to charge movement within the battery structure. Thin film ion batteries hold the promise of much higher energy densities than are possible from conventional wet chemistry batteries.

Ion batteries can be prepared from macroscopic compounding techniques to fabricate anode, cathode, and electrolyte materials which are then bonded together to form the battery (the so called "thick film" technique), or by depositing thin films of such materials using vacuum techniques, producing "thin film" batteries. The fabrication of batteries by "thick film" techniques is usually directed toward high current capacity devices. Thin film batteries are generally employed in low current draw applications in which space and weight must be conserved.

U.S. Pat. No. 5,895,731 (hereinafter "the '731 patent") to Clingempeel is exemplary of batteries fabricated using "thick film" construction. The '731 patent teaches the preparation of a cathode from a mixture of powders of titanium nitride, selenium, silicon, and buckminsterfullerene bonded together with epoxy polymer to aluminum foil. Additionally the '731 patent teaches the preparation of an anode from lithium foil, fiberglass matting and n-methyl-pyrrolidone, and the preparation of an electrolyte layer by gelation of a mixture of n-methyl-pyrrolidone, lithium metal, and polyimide powder to produce a cross-linked lithium gel electrolyte which is cast into a sheet. These materials are pressed together and sealed in polyimide plastic with appropriate electrical contacts to the anode and cathode. Production of such a battery requires strict atmospheric control during fabrication to exclude moisture and oxygen, and numerous preparatory steps.

Thin film battery fabrication techniques are well known to those skilled in the art. Thus, for example, U.S. Pat. No. 5,338,625 to Bates (hereinafter "the '625 patent"), teaches the formation of a lithium based thin film battery by vacuum deposition of two co-planar vanadium current collectors on an insulating substrate. Upon one of the current collectors is deposited a cathode comprising an amorphous vanadium oxide layer. This cathode layer is deposited by reactive ion sputtering from a vanadium target in an oxygen environment. On top of the cathode layer is deposited an amorphous lithium phosphorous oxynitride (also called "Substoichiometric lithium phosphorous oxynitride") layer which acts as an electrolyte. This layer is deposited by reactive ion sputtering of lithium orthophosphate in a nitrogen atmosphere. Finally, a layer of lithium metal was vacuum evaporated onto the assembly, covering both the bare current collector and the current collector bearing the cathode and electrolyte. The disclosed thin film battery contains a bare lithium anode, and as such requires further steps to isolate the anode from the ambient environment. Additionally, because of the presence of the relatively low melting lithium metal the disclosed battery has low tolerance for heating.

Hybrid batteries containing a combination of elements prepared by macroscopic compounding techniques which in

turn have thin films deposited onto them have also been described. Thus, U.S. Pat. Nos. 5,569,520 (hereinafter "the '520 patent") and 5,612,152 (hereinafter "the '152 patent"), both to Bates, describe a preparation of a lithium manganate cathode pellet using traditional ceramic processing techniques (e.g., hot pressing and sintering the powder). The pellet is then subjected to deposition of a thin electrolyte film of, e.g., lithium phosphorous oxynitride (Sub-stoichiometric lithium phosphorous oxynitride), by reactive ion sputtering using the techniques described above for the '625 patent to Bates. A lithium film anode is then deposited on the exposed face of the electrolyte film, again by vacuum techniques, forming a multilayered thin film battery. The '520 and '152 patents further disclose that an additional mass of lithium can be incorporated into the battery by sandwiching the anode of the multi-layered battery material described above with an additional sheet of lithium foil and cycling the sandwiched construction through several charging/discharging cycles. In this process, the thin lithium film is "plated" onto the foil sandwiched with it to form a continuous phase with the electrolyte/lithium metal interface, bonding the lithium foil into the multi-layered material.

The '152 and '520 patents further disclose that deposition of a lithium anode film on the exposed face of the electrolyte of a multi-layer battery material can be eliminated for the process of bonding a foil sandwiched to the multi-layer battery material. These patents disclose that pressing a piece of lithium foil against the exposed face of the electrolyte layer of the multi-layer battery material and cycling the battery between charged and discharged states will also bond the lithium foil to the multi-layer battery material by virtue of deposition of lithium metal from the electrolyte during battery charging onto the face of the lithium foil in contact with the electrolyte.

Finally, the '152 and '520 patents teach that deposition of an anode can be dispensed with. Batteries can be fabricated by vacuum application of an electrolyte film onto a cathode material and the application of a current collector onto the exposed side of the electrolyte film. Cycling the battery through a charge cycle electrochemically deposits a lithium anode layer between the current collector and the electrolyte. Thus, a thin film of Sub-stoichiometric lithium phosphorous oxynitride was deposited by vacuum evaporation onto a Li_2MnO_4 cathode pellet, forming a Sub-stoichiometric lithium phosphorous oxynitride film coating on one face of the cathode. Onto the exposed face of the Sub-stoichiometric lithium phosphorous oxynitride film coating a current collecting layer of vanadium metal was deposited. This multi-layer battery material was subjected to a charging current, whereupon lithium metal was extracted from the electrolyte layer and plated onto the face of the vanadium current collector in contact with the electrolyte film.

Additional disclosure of the technique of electrochemical deposition of a lithium metal anode within the multi-layer structure of an electrolyte and cathode material has been described in PCT application US00/06997 of Lockheed Martin Energy Research Corporation, filed 17 Mar. 2000 (hereinafter, "the '997 application"). This application teaches the formation of a multi-layer battery material by sequential deposition of various thin films onto an insulating substrate. In this manner, a cathode current collector in the form of an Ag or Pt thin film was first deposited onto an alumina substrate. Following this a cathode film of Li_2MnO_4 was deposited onto the current collector by vacuum sputtering techniques. Onto the cathode film was deposited an electrolyte thin film of Sub-stoichiometric lithium phosphorous oxynitride by reactive ion sputtering. Onto the exposed

face of the Sub-stoichiometric lithium phosphorous oxynitride electrolyte film was deposited a metal thin film to serve as an anode current collector. The metal was selected from metals that do not form intermetallic compounds with lithium, generally the group 8 transition metals, Ti, aluminum, gold, and in particular the refractory metals, as will be known to one skilled in the art.

Thus fabricated, this multi-layer battery material was subject to a charging current whereby a lithium anode was plated between the current collector thin film and the electrolyte. The '997 application further teaches that a protective layer must be deposited onto the current collector for the electrochemical anode deposition/stripping to be reversible. In this role, deposition of films of lithium nitride or Sub-stoichiometric lithium phosphorous oxynitride onto the exposed face of the anode current collector film as protective layers is taught. The '997 application discloses that this over-layer functions to prevent lithium chemical attack upon the current collector, prevent undesirable morphology from occurring in the deposited lithium layer (a so called "fluffy" or "mossy" morphology), and to absorb the volume change thought to accompany the deposition of the lithium metal layer. The over-layer is said to additionally impart electrical insulation, mechanical protection, and act as a barrier to moisture and oxygen for the lithium layer.

While the plated lithium anode prior art has addressed some of the problems associated with the $\text{Li}/\text{LiM}_x\text{O}_y$ couple (where M =a transition metal), such as the heat sensitivity of lithium metal and some of the difficulties due to the air sensitive nature of lithium (see U.S. Pat. No. 5,871,865 to Barker et. al. for a discussion of these and other problems arising from the presence of lithium metal in the preparation of batteries) there is still some inherent instability in lithium based batteries constructed according to disclosures in the prior art. This instability can be addressed by the addition of a protective layer to the anode current collector. Such a solution increases the bulk of a battery, reducing its current density, and adds a processing step, increasing its cost, without increasing the net capacity or performance of the battery.

The process of the present invention for production of a multi-layer thin film battery precursor structure is directed to eliminating the need for an additional protective layer applied to the anode or anode current collector and to increasing the amount of lithium that may be electrochemically formed as an anode during activation of an "anodeless" battery precursor in the manner of Bates.

The present invention is directed toward minimizing the number of processing steps required to fabricate a thin film battery, and at increasing charge retention in a battery and the number of charge/discharge cycles that a battery can be subjected to without significant degradation. Additionally, the present invention seeks to provide a method of producing a lithium based battery which is air stable without the application of a protective overlayer following the formation of the anode, cathode, and electrolyte layers and charging of such a battery.

One aspect of the present invention is a process of producing a secondary, lithium based, thin film battery, having the steps of:

- a) depositing a film comprising a solid state electrolyte material that is a conductor of lithium ions onto an exposed, conductive face of a substrate;
- b) depositing a film of a transition metal oxide onto the electrolyte material;
- c) forming a cathode film layer by lithiating the transition metal oxide film until it contains a supra-stoichiometric amount of lithium;

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d) depositing an electron-conductive current collector film upon the cathode film layer;

e) forming a lithium metal buried anode layer between the conductive face of the substrate and the solid state electrolyte material using a flowing current between the substrate conductive face and the cathode current collector, in the process oxidizing the cathode film layer and causing lithium ions to migrate into and through the solid state electrolyte material, and then to be reduced to lithium metal and forming said buried anode layer; and

f) maintaining the current flow until the buried anode layer contains a desired amount of lithium metal.

Another aspect of the present invention are lithium thin film batteries with buried anodes and reverse structures made according to the above process.

Another aspect of the present invention is a process for producing a lithium based, thin film battery precursor composite structure, comprising the steps of:

a) depositing a film comprising a solid state electrolyte material that is a conductor of lithium ions onto an exposed, conductive face of a substrate;

b) depositing a film comprising a transition metal oxide on top of the film of solid state electrolyte material;

c) forming a cathode film layer by lithiating the transition metal oxide film until it contains a supra-stoichiometric amount of lithium; and

d) depositing a current collector film upon an exposed face of said cathode film layer, said current collector comprising an electron conducting material.

Another aspect of the present invention are lithium battery precursor composite structures made according to the process for producing battery precursor composite structures recited above.

Another aspect of the present invention is a lithium battery composite precursor, characterized by its ability to form a buried lithium anode layer at the interface between an anode current collector and an electrolyte when a current is maintained between the anode current collector and the cathode current collector, and its ability to be chemically stable when exposed to an ambient environment, the precursor having an anode current collector layer that forms a support and has at least one conductive face; an electrolyte layer that is a conductor of lithium ions and has one face in communication with a conductive face of the anode current collector layer; a cathode layer that is in communication with a face of the electrolyte layer that is not in communication with the anode current collector layer; and a cathode current collector layer that is in communication with a face of the cathode layer that is not in communication with the electrolyte layer.

Another aspect of the present invention is a lithium thin film battery having an anode current collector layer that forms a support and has at least one conductive face; a buried anode layer comprising lithium metal in communication with a conductive face of said anode current collector; an electrolyte that is a conductor of lithium ions and is in communication with said anode layer; a cathode layer that is in communication with a face of said electrolyte layer that is not in communication with said anode layer; and a cathode current collector layer that is in communication with a face of the cathode layer that is not in communication with the electrolyte layer, the battery being characterized by an increase in the amount of metallic lithium contained in its buried anode layer upon charging and a reduction in the amount of lithium metal in its buried anode layer upon

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discharging, and its chemical stability when exposed to an ambient environment in any state of charge.

Other aspects of this invention will appear from the following description and appended claims, reference being made to the accompanying drawings forming a part of this specification wherein like reference characters designate corresponding parts in the several views.

BRIEF DESCRIPTION OF DRAWINGS

Before explaining the disclosed embodiments of the present invention in detail, it is to be understood that the invention is not limited in its application to the details of the particular arrangement shown, since the invention is capable of other embodiments. Also, the terminology used herein is for the purpose of description and not of limitation.

FIG. 1: A Deposition Sequence Resolved Cross-Sectional Elevation View Of a Prior Art Thin Film Battery.

FIG. 2: A Cross-Sectional Elevation View Of a Battery Precursor Composite Structure.

FIG. 3: A Cross-Sectional Elevation View Of a Thin Film Battery Formed By Activation Of a Precursor Composite Structure.

FIG. 4: A Graph of the Charge Capacity of a Battery of the Present Invention as a Function of Charge/Discharge Cycle Number.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

The present invention is directed to a lithium based thin film secondary battery. The thin film battery of the present invention can be fabricated by sequential vapor deposition techniques to effect the application of the several film layers required to form a complex structure (herein after, "battery precursor composite structure"). The battery precursor composite structure is then subjected to an activation step, and thereafter functions as a thin film lithium based battery.

The process of the present invention utilizes three vapor deposition steps to produce an air stable composite structure having a current collector layer, a cathode layer, and an electrolyte layer upon a conductive substrate. The order of these layers, as viewed from the conductive substrate, is reversed from that of conventional thin film batteries, which will be further elucidated below. The conductive substrate of the battery precursor composite structure serves as both a support for the precursor composite structure and, upon activation, as an anodic current collector in the resultant thin film battery. The various layers comprising the present invention battery structure can be deposited using one or more such techniques as will be familiar to one skilled in the art, for example, evaporation, sputtering, chemical vapor deposition, and the like.

The battery precursor composite structure is both oxygen and water vapor stable and thermally robust. As a consequence the battery precursor composite structure can be manipulated without isolation from the ambient environment and can withstand the elevated temperatures associated with electronic device processing. Thus, for example, the battery precursor composite structure of the present invention can withstand incorporation into circuit boards or other electronic or electrical subassemblies prior to soldering and/or encapsulation of the subassembly without utilizing any special environment, isolation steps, or heat sinking devices to protect it.

The battery precursor composite structure can be activated using an initial charging step in which a lithium metal

anode is formed between the support and the electrolyte, thereby producing a lithium-based thin film battery which is characterized by having the lithium metal layer buried in the structure of the battery (hereinafter, "buried anode structure") and requiring no additional layer to protect it from the ambient environment. This battery can be returned to the battery precursor composite structure state by completely discharging it, thereby consuming the anode and returning it to its "as deposited" battery precursor composite structure state.

With reference to FIG. 1, the prior art preparation of lithium based thin film secondary batteries begins with a substrate **100**, typically an insulator comprising a metal oxide, upon which is deposited a cathode conductive current collector layer **101**. The cathode current collector is chosen for high conductivity and chemical inertness, and is typically a metal. Metals used in the prior art for this purpose include platinum or gold.

Onto current collector layer **101** is deposited a cathodic electrode material **102**. Cathodic electrode material **102**, in the case of a lithium battery, is typically a lithium intercalation compound capable of reversibly ejecting lithium ions as the compound is oxidized, and injecting lithium ions as the compound is reduced. Examples of such compounds are lithium manganate (LiMn_2O_4), lithium nickelate (LiNiO_2), and lithium vanadate (LiV_2O_5). Other lithiated transition metal oxides have also been employed for this purpose.

Next, a solid state electrolyte layer **103** is deposited upon the cathodic electrode layer **102**. Solid electrolyte **103** is chosen for its stability in contact with lithium metal and its ability to be a facile conductor of lithium ions between cathode **102** and anode **104**. Typically, substoichiometric lithium phosphorous oxynitride is used as an electrolyte layer. Substoichiometric lithium phosphorous oxynitride is a family of materials having the general formula $\text{Li}_x\text{PO}_y\text{N}_z$. In the "as deposited" state, the material has values for x and y of about 3, and for z of about 1.5.

Onto electrolyte layer **103** is next deposited a layer of lithium metal which serves as anode **104**. Some prior art devices include a barrier layer **107**, chosen to be impermeable to Li atoms, is interposed between electrolyte layer **103** and lithium metal anode **104**. The barrier layer prevents chemical attack upon the electrolyte layer by Li. In the case where Sub-stoichiometric lithium phosphorous oxynitride is chosen as the electrolyte layer, barrier layer **107** is not needed.

Anode layer **104** is next deposited, either onto the exposed face of barrier layer **107**, if it is used, or directly onto the exposed face of electrolyte layer **103**, if barrier layer **107** is not used. In a lithium based battery, anode layer **104** is a lithium metal thin film.

Anode current collector **105** is then deposited onto anode **104**. The anode current collector is chosen to preclude formation of lithium intermetallic compounds, and is selected from group 8 transition metals, Ti, and noble metals.

Finally, anode protection layer **106** is deposited onto current collector layer **105**. Anode protection layer **106** is typically a second layer of Sub-stoichiometric lithium phosphorous oxynitride or another moisture and electron impervious layer such as AlN. A typical thin film battery requires between five and seven deposition steps, at least one of which is carried out primarily to shield battery elements comprised of lithium metal from the ambient environment.

The sequence of the prior art deposition steps is chosen to minimize the problems associated with having a thermally

labile and reactive species, such as lithium metal present during deposition of subsequent layers, as would be the case if the above described deposition sequence were to be reversed, with a layer of lithium metal being deposited first and the remaining layers deposited on top of it.

If the lithium metal anode is eliminated, the prior art teaches that one may be formed electrochemically "in situ" by utilizing lithium contained in the cathode material. Such a scheme does not permit the formation of anodes with lithium present in supra-stoichiometric amounts relative to the cathodic material. Because the amount of lithium which can be incorporated into the anode is limited in this manner, the volumetric energy capacity of the battery can't be maximized. Additionally, the prior art suggests that the overlayer material must be selected to provide for volume changes in the anode layer during charging and discharging and to prevent undesirable morphology in the anode material as it is formed. If this is not done, battery failure will follow charging and discharging of the battery.

With reference to FIG. 2, the deposition of a reverse structure battery precursor composite structure **200** can be carried out in three deposition steps, building the functional layers up upon the anode current collector of the device. Thus, anode current collector (hereinafter, "substrate") **201** is chosen for its electrical conductivity and its inert character toward attack by lithium metal, as well as its ability to function as a support for the other layers deposited onto it. Substrate **201** may be, for example, a refractory metal, examples of which are copper and nickel. Substrate **201** may also be a ferrous alloy, for example steel, by way of example, stainless steel, for example type 430, also designated as ASTM A176 and type 304, also designated as type A167, which are articles of commerce recognized by those of ordinary skill in the art as an alloy which comprises also chrome. Substrate **201** may also be a layer of any other conductive metal that is compatible with lithium metal, for example iron, or any transition metal that does not form intermetallic compounds with lithium. Substrate **201** can also comprise a non-electrical conductor, for example glass or a plastic, such as will be familiar to those of ordinary skill in the art, for example, polyester onto which a conductive film has been deposited, for example gold.

Onto substrate **201** is deposited an electrolyte film layer **204**. Electrolyte film layer **204** is chosen for its ability to be a facile conductor of lithium ions and for its stability when in contact with lithium metal. The electrolyte may be any solid state electrolyte that can be deposited by vacuum techniques that fulfills the criterion of facile lithium ion conduction and inertness toward lithium metal, but the preferred electrolyte is lithium phosphorous oxynitride (Sub-stoichiometric lithium phosphorous oxynitride) as defined above.

Onto the exposed face of electrolyte film **204** (the face of the film layer that is not in contact with substrate **201**) is deposited cathode layer **203**. The material from which cathode layer **203** is formed may be any of the lithium intercalate materials which can reversibly eject lithium ions upon (LiMn_2O_4), lithium nickelate (LiNiO_2), and lithium vanadate (LiV_2O_5). These films can be deposited from sources containing lithium with subsequent elimination of the lithium insertion step, or from the transition metal oxide which is then subjected to a lithium insertion step.

The preferred method of fabricating cathode layer **203** is to deposit a transition metal oxide layer of desired thickness followed by lithiation of the transition metal oxide. This process permits a cathode layer **203** thus formed to contain

a supra-stoichiometric amount of lithium which can be made available for formation of a lithium anode when battery precursor composite structure **200** is subjected to an activation step (described below). Lithiation of the oxide film can be accomplished by treating the transition metal oxide film with lithium vapor. It will be appreciated by one of skill in the art, that a transition metal oxide containing supra-stoichiometric amounts of lithium is more stable upon thermal exposure and upon exposure to the ambient environment than structures of the same type containing free lithium metal layers.

The preferred transition metal from which the oxide layer is formed is vanadium. A suitable vanadium oxide-based cathode layer **203** can be formed by first depositing a layer of V_2O_5 onto the exposed face of electrolyte layer **204** by, for example, reactive ion sputtering from a vanadium target in the presence of oxygen. Following this step, lithium metal can be vacuum evaporated onto the vanadium oxide layer, thus lithiating the oxide layer.

Other vacuum techniques as will be familiar to one skilled in the art can be employed to deposit various layers of the present invention battery. In particular, several techniques familiar to those of skill in the art can be used to deposit cathode layer **203**, both in cases where the layer is a stoichiometric lithium transition metal oxide, and in cases where the layer contains a supra-stoichiometric amount of lithium metal.

In a fourth step following two film deposition steps and the lithiation step, a cathode current collector film **202** is deposited onto cathode film **203**. Although cathode current collector film **202** may be any electrically conductive metal that is inert toward the cathode material, aluminum and copper are preferred.

A battery of the type shown in cross-section in FIG. 3 is formed by activating the multi-layer battery precursor composite structure **200**. Multi-layer battery precursor composite structure **200** is activated by applying a source of sufficient electromotive force (emf) of constant polarity between substrate **201** and the cathode current collector layer **202**. With reference to FIG. 3, in this manner, material in cathode layer **203** is oxidized. During this oxidation, lithium ions are ejected from cathode layer **203** and are conducted through the electrolyte layer **204**. The lithium ions are subsequently electrochemically reduced to lithium metal at the electrolyte **204**/support **201** interface, thus forming the buried lithium metal anode layer **305**. This layer is termed buried because it is formed in such a manner that it is never exposed to the ambient environment, but is instead formed within the structure of the battery precursor composite material, and protected afterward by the thick conductive support **200** beneath it (as FIG. 3 is drawn) and by the other multiple layers above it. Current is passed into the device in this manner until a lithium anode layer of sufficient thickness has been formed.

Once the activation step is completed, thus depositing buried anode layer **305** of the desired thickness, battery **300** has a configuration which is inverted from that of the conventional lithium thin film battery (hereinafter, "reverse configuration"). This reverse configuration provides for a "buried anode" structure that both protects the anode, without additional protective layers, and provides for a battery that withstands exposure to the ambient environment and can withstand thermal excursions without deterioration.

EXAMPLE 1

A coupon of type 430 stainless steel (an article of commerce also known to those of ordinary skill in the art as

ASTM A176, an alloy having 16 wt. % chromium or more) was cut from sheet stock obtained from Teledyne Rodney Metals, Inc., New Bedford, Mass. The coupon was prepared for use as an anode current collector/substrate **201** by washing the stainless steel in a detergent solution, rinsing with deionized water, followed by an additional ethyl alcohol rinse, and drying in room air. The detergent employed was Alkanox, a commercial detergent for cleaning laboratory glassware, but any neutral detergent formulated for such purpose can alternatively be employed.

Thus prepared, the substrate was placed into a vacuum chamber containing a target of Li_3PO_4 . The chamber was evacuated to 10^{-5} torr and a Sub-stoichiometric lithium phosphorous oxynitride film of 1.0 nm-thick electrolyte layer **204** was formed upon the exposed face of the stainless steel substrate by reactive ion sputtering in 20 millitorr of nitrogen gas using a RF power setting of 4–5 W/cm².

A 500 nm-thick cathode film **203** was next formed by first depositing a vanadium oxide film onto the electrolyte film. This vanadium oxide thin film was deposited by thermal evaporation of a corresponding V_2O_5 powder source.

Thus formed, the vanadium oxide layer was then lithiated by exposing the vanadium oxide layer to lithium vapor. Lithium vapor was obtained by thermal evaporation of pure Li metal onto the V_2O_5 layer at room temperature in a 10^{-5} mbar vacuum. Upon contact with the vanadium oxide film, lithium diffuses into the vanadium oxide material, forming a lithium vanadium oxide cathode. Treatment with lithium vapor was continued until a material approximating the formula $Li_xV_2O_5$ was obtained, wherein $X \geq 3$.

Onto the lithiated vanadium oxide layer was deposited a 200–300 nm layer of aluminum metal by vacuum evaporation to act as the cathode current collector **202**.

Thus prepared, the multi-layered battery precursor composite structure **200** was removed from the vacuum chamber and connected to a Arbin potentio-galvanostat to apply a constant current and monitor voltage changes. Current was applied to the multi-layered material until the cell voltage reached about 3.8 V vs. Li. In this manner a buried lithium anode was created forming a thin-film battery which could be handled in the ambient environment without further isolation. The discharge capacity of this battery was about 25 mAh/cm² which corresponds to 1.4 Li per mole of V_2O_5 .

EXAMPLE 2

The battery device of Example 1 was subjected to cyclic testing for over 750 charge/discharge cycles. This was accomplished by charging and discharging the battery under conditions in which charging current having a current density of 0.1 mA/cm² was applied until a potential of about 3.8 V vs lithium was observed across the battery. Discharge cycles were carried out at the same current density and continued until a potential of about 2.0 V vs lithium was observed across the battery. The results are presented in FIG. 4. It can be seen that the capacity of the battery did not appreciably change in over 800 such charge/discharge cycles. The battery retained its ability to be handled in the ambient environment throughout the charge/discharge test.

Although the present invention has been described with reference to preferred embodiments, numerous modifications and variations can be made and still the result will come within the scope of the invention. No limitation with respect to the specific embodiments disclosed herein is intended or should be inferred.

What is claimed is:

1. A process for producing a secondary, lithium based, thin film battery, the process comprising the steps of:

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- a) depositing a film comprising a solid state electrolyte material onto an exposed, conductive face of a substrate, wherein the solid state electrolyte material is a conductor of lithium ions;
- b) depositing a film of a transition metal oxide upon an exposed face of said film of solid state electrolyte material;
- c) lithiating said transition metal oxide film until it contains a supra-stoichiometric amount of lithium, thus forming a cathode film layer;
- d) depositing a current collector film upon an exposed face of said cathode film layer, said current collector comprising an electron conducting material;
- e) forming a buried anode layer comprising lithium metal between said conductive face of said substrate and said solid state electrolyte material by flowing a current between said substrate conductive face and said cathode current collector, whereby said cathode film layer is oxidized, causing lithium ions to migrate into and through said solid state electrolyte material, thence being reduced to lithium metal and forming said buried anode layer; and
- f) maintaining said current flow until said buried anode layer contains a desired amount of lithium metal.

2. The process of claim 1, wherein techniques used to deposit said films are selected from vacuum evaporation and reactive sputtering.

3. The process of claim 1, wherein said solid state electrolyte film comprises Sub-stoichiometric lithium phosphorous oxynitride.

4. The process of claim 3, wherein said cathode film is selected from lithium vanadate, lithium manganate, lithium nickelate, and lithium cobaltate.

5. The process of claim 1, wherein said substrate is selected from stainless steel, plastic bearing a conductive coating on at least one face, and glass bearing a conductive coating on at least one face.

6. The process of claim 1, wherein said cathode current collector is selected from aluminum, gold, and refractory metal.

7. A process for producing a secondary, lithium based, thin film battery, the process comprising the steps of:

- a) depositing a film comprising a solid state electrolyte material onto an exposed, conductive face of a substrate, wherein the solid state electrolyte material is a conductor of lithium ions;
- b) depositing a cathode film comprising a lithiated transition metal oxide upon an exposed face of said film of solid state electrolyte material;
- c) depositing a current collector film upon an exposed face of said cathode film layer, said current collector comprising an electron conducting material;
- d) forming a buried anode layer comprising lithium metal between said conductive face of said substrate and said solid state electrolyte material by flowing a current between said substrate conductive face and said cathode current collector, whereby said cathode film layer is oxidized, causing lithium ions to migrate into and through said solid state electrolyte material, thence being reduced to lithium metal and forming said buried anode layer; and
- e) maintaining said current flow until said buried anode layer contains a desired amount of lithium metal.

8. The process of claim 7, wherein techniques used to deposit said films are selected from vacuum evaporation and reactive sputtering.

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9. The process of claim 7, wherein said solid state electrolyte film comprises Sub-stoichiometric lithium phosphorous oxynitride.

10. The process of claim 9, wherein said cathode film is selected from lithium vanadate, lithium manganate, lithium nickelate, and lithium cobaltate.

11. The process of claim 7, wherein said substrate is selected from stainless steel, plastic bearing a conductive coating on at least one face, and glass bearing a conductive coating on at least one face.

12. The process of claim 7, wherein said cathode current collector is selected from aluminum, gold, and refractory metals.

13. A process for producing a secondary, lithium based, thin film battery, the process comprising the steps of:

- a) depositing a film comprising lithium phosphorous oxynitride on an exposed face of type 430 stainless steel substrate by reactive ion sputtering from a target of Li_3PO_4 in nitrogen, thereby forming a lithium phosphorous oxynitride electrolyte film bonded to one face of said stainless steel substrate;
- b) forming a cathode film comprising lithium vanadate bonded to an exposed face of said lithium phosphorous oxynitride;
- c) depositing a film comprising copper metal upon an exposed face of said lithium vanadate cathode film, thereby forming a cathode current collection bonded to said lithium vanadate cathode film;
- d) forming a buried anode layer comprising lithium metal between said stainless steel substrate and said lithium phosphorous oxynitride electrolyte film by flowing a current between said stainless steel substrate and said cathode current collector, whereby said cathode film layer is oxidized, causing lithium ions to migrate into and through said solid state electrolyte material, thence being reduced to lithium metal and forming said buried anode layer; and
- e) maintaining said current flow until said buried anode layer contains a desired amount of lithium metal.

14. A process for producing a secondary, lithium based, thin-film battery, the process comprising the steps of:

- a) depositing a film comprising lithium phosphorous oxynitride on the exposed face of a type 304 stainless steel substrate by reactive ion sputtering from an LiPO_4 target in nitrogen, thereby forming a lithium phosphorous oxynitride electrolyte film bonded to said stainless steel substrate face;
- b) depositing a film comprising vanadium oxide upon an exposed face of said lithium phosphorous oxynitride film by thermal evaporation from vanadium oxide powder, thereby forming a vanadium oxide film bonded to said phosphorous oxynitride film;
- c) exposing said vanadium oxide film to lithium metal vapor, thereby forming a lithium vanadate cathode film;
- d) depositing a film comprising copper metal upon an exposed face of said lithium vanadate cathode film, thereby forming a cathode current collector bonded to said lithium vanadate cathode film;
- e) forming a buried lithium anode layer between said stainless steel substrate and said lithium phosphorous oxynitride electrolyte film by flowing a current between said substrate and said cathode current collector, whereby said lithium vanadate cathode film is oxidized, causing lithium ions to migrate into and through said lithium phosphorous oxynitride electrolyte film, thence

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being reduced to lithium metal and forming said buried anode layer; and

f) maintaining said current flow until said buried anode layer contains a desired amount of lithium metal.

15. The process of claim 14, wherein said vanadium oxide film is exposed to sufficient lithium vapor to form a film having the formula $\text{Li}_x\text{V}_2\text{O}_5$ where x is about 3 or greater.

16. A process for producing a lithium based, thin film secondary battery precursor composite structure, the process comprising the steps of:

a) depositing a film comprising a solid-state electrolyte material onto an exposed, conductive face of a substrate, wherein the solid state electrolyte material is a conductor of lithium ions;

b) depositing a film comprising a transition metal oxide upon an exposed face of said film of solid state electrolyte material;

c) lithiating said transition metal oxide film until it contains a supra-stoichiometric amount of lithium, thus forming a cathode film layer; and

d) depositing a current collector film upon an exposed face of said cathode film layer, said current collector comprising an electron conducting material.

17. The process of claim 16, wherein techniques used to deposit said films are selected from vacuum evaporation and reactive sputtering.

18. The process of claim 16, wherein said solid state electrolyte film is sub-stoichiometric lithium phosphorous oxynitride.

19. The process of claim 18, wherein said cathode film layer is selected from lithium vanadate, lithium manganate, lithium nickelate, and lithium cobaltate.

20. The process of claim 16, wherein said substrate is selected from stainless steel, plastic bearing a conductive coating on at least one face, and glass bearing a conductive coating on at least one face.

21. The process of claim 16, wherein said cathode current collector is selected from aluminum, gold, and refractory metals.

22. A process for producing a lithium based, thin film secondary battery precursor composite structure, the process comprising the steps of:

a) depositing a film comprising a solid state electrolyte material onto an exposed, conductive face of a substrate, wherein the solid state electrolyte material is a conductor of lithium ions;

b) depositing a cathode film comprising lithiated transition metal oxide upon an exposed face of said film of solid state electrolyte material; and

c) depositing a current collector film upon an exposed face of said cathode film layer, said current collector comprising an electron conducting material.

23. The process of claim 22, wherein techniques used to deposit said films are selected from vacuum evaporation and reactive sputtering.

24. The process of claim 22, wherein said solid state electrolyte film is sub-stoichiometric lithium phosphorous oxynitride.

25. The process of claim 24, wherein said cathode layer is selected from lithium vanadate, lithium manganate, lithium nickelate, and lithium cobaltate.

26. The process of claim 22, wherein said substrate is selected from a stainless steel, a plastic bearing a conductive coating on at least one face, and a glass bearing a conductive coating on at least one face.

27. The process of claim 22, wherein said cathode current collector is selected from aluminum, gold, and refractory metals.

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28. A process for producing a lithium based, thin film secondary battery precursor composite structure, the process comprising the steps of:

a) depositing a film comprising lithium phosphorous oxynitride on an exposed face of a type 430 stainless steel substrate by reactive ion sputtering from a target of Li_3PO_4 in nitrogen, thereby forming a lithium phosphorous oxynitride electrolyte film bonded to one face of said stainless steel substrate;

b) forming a cathode film comprising lithium vanadate bonded to an exposed face of said lithium phosphorous oxynitride; and

c) depositing a film comprising copper metal upon an exposed face of said cathode film, thereby forming a cathode current collector bonded to said lithium vanadate cathode film.

29. A process for producing a lithium based, thin film secondary battery precursor composite structure, the process comprising the steps of:

a) depositing a film comprising lithium phosphorous oxynitride on the exposed face of a type 430 stainless steel substrate by reactive ion sputtering from an Li_3PO_4 target in nitrogen, thereby forming a lithium phosphorous oxynitride electrolyte film bonded to said stainless steel substrate face;

b) depositing a film comprising vanadium oxide upon an exposed face of said lithium phosphorous oxynitride film by thermal evaporation from vanadium oxide powder, thereby forming a vanadium oxide film bonded to said phosphorous oxynitride film;

c) exposing said vanadium oxide film to lithium metal vapor, thereby forming a lithium vanadate cathode film; and

d) depositing a film comprising copper metal upon an exposed face of said lithium vanadate cathode film, thereby forming a cathode current collector bonded to said lithium vanadate cathode film.

30. The process of claim 29, wherein said vanadium oxide film is exposed to sufficient lithium vapor to form a film having a composition $\text{Li}_x\text{V}_2\text{O}_5$, where x is about 3 or greater.

31. The process of claim 3, wherein said cathode film is lithium vanadate.

32. The process of claim 3, wherein said cathode film is lithium manganate.

33. The process of claim 3, wherein said cathode film is lithium nickelate.

34. The process of claim 3, wherein said cathode film is lithium cobaltate.

35. A lithium based, thin film secondary battery precursor composite structure produced by the process comprising the steps of:

a) depositing a film comprising a solid state electrolyte material onto an exposed, conductive face of a substrate, wherein the solid state electrolyte material is a conductor of lithium ions;

b) depositing a film comprising a transition metal oxide upon an exposed face of said film of solid state electrolyte material;

c) lithiating said transition metal oxide film until it contains a supra-stoichiometric amount of lithium, thus forming a cathode film layer; and

d) depositing a current collector film upon an exposed face of said cathode film layer, said current collector comprising an electron conducting material.

36. A secondary, lithium based, thin film battery produced by the process comprising the steps of:

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- a) depositing a film comprising a solid state electrolyte material onto an exposed, conductive face of a substrate, wherein the solid state electrolyte material is a conductor of lithium ions;
- b) depositing a film of a transition metal oxide upon an exposed face of said film of solid state electrolyte material;
- c) lithiating said transition metal oxide film until it contains a supra-stoichiometric amount of lithium, thus forming a cathode film layer;
- d) depositing a current collector film upon an exposed face of said cathode film layer, said current collector comprising an electron conducting material;

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- e) forming a buried anode layer comprising lithium metal between said conductive face of said substrate and said solid state electrolyte material by flowing a current between said substrate conductive face and said cathode current collector, whereby said cathode film layer is oxidized, causing lithium ions to migrate into and through said solid state electrolyte material, thence being reduced to lithium metal and forming said buried anode layer; and
- f) maintaining said current flow until said buried anode layer contains a desired amount of lithium metal.

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